JLMN-Journal of Laser Micro/Nanoengineering Vol. 3, No. 3, 2008

Fabrication of Moulds and Dies Using Precision Laser Micromachining and Micromilling Technologies

Evgueni BORDATCHEV and Suwas NIKUMB

Industrial Materials Institute
National Research Council of Canada
800 Collip Circle, London, Ontario N6G 4X8, Canada
E-mail: {evgueni.bordatchev, suwas.nikumb}@nrc.gc.ca

This paper presents results obtained from our studies on the 3D laser micromachining and micromilling technologies. Specific examples of micro moulds and dies, fabricated using these techniques, are presented. The layer-by-layer material removal for 3D precision laser micromachining was proposed and the required process parameters were identified. Specifically, the process parameters, such as overlap between grooves and number of passes per layer, were investigated. The results were then applied to fabricate a "Cross Sign" die with overall dimensions of 2.5x2.5 mm and a wall width of 50 μm in mild steel A20 material. The finished micro die had a surface roughness of <0.35 μm and contour geometric errors within +/-2 μm. For comparison purpose, the same "Cross Sign" microdie was fabricated using the micromilling process from brass and replicated on PMMA through the hot embossing process. Geometric errors within +/-1 μm and a surface roughness inside the rectangular channels of 9.9 nm were achieved. The paper discusses challenges met during fabrication of the dies along with a comparative analysis of the geometric quality.

DOI: 10.2961/jlmn.2008.03.0009

Keywords: micro moulds and dies, laser micromachining, micromilling, methodology, optimization

1. Introduction

The world-wide demand for miniaturization of components and sub-assemblies with complex 3D structures and geometric features in the range of a few microns is evident in a number of manufacturing applications such as miniature biomedical devices, automotive parts, micro components and systems. In this respect, micro material removal processes such as laser micromachining, micromilling, micro electro-discharge machining, microgrinding and other micromachining technologies offer significant advantages towards the development of microfabrication technologies applied in the mass production of micro parts using conventional processes.

2. Precision laser micromachining of moulds and dies

Precision laser micromachining provides a unique solution to fabricate micro moulds and dies for mass production, e.g. using injection moulding and/or hot embossing processes [1-3]. The laser micromachining process offers four major advantages over conventional technologies. First of all, a laser beam can be used as a sharp material removal tool, which can be focused down to 1 μm in diameter. Secondly, a wide range of materials can be machined, e.g. from glass and plastics to difficult-to-machine materials such as tool steels and ceramics. Also, combined with a high precision motion system a tightly focussed beam can remove precise amounts of material with high accuracy and precision. Finally, laser micromachining is an environmentally friendly process compared to chemical etching processes. In addition, the laser beam can be controlled effectively in terms of focal spot diameter, working distance, pulse energy and beam shape to optimize the material-removal process [4-7]. Recent advances in the development of laser micromachining technology can also be considered while machining of 2½D and 3D parts, e.g. micro mould and dies, that require high level of control of the process parameters and where laser beam can be used as an "adjustable cutting tool" with changing geometry. When a laser beam is focused on to the material surface, it has the smallest diameter with compact distribution of pulse energy that is more suitable for drilling, cutting and trimming operations [8]. When the focal point is above the material surface, the laser beam at the working distance has a significantly wider diameter and energy distribution, which is more suitable for depth controlled material removal operations and finishing processes such as laser polishing, surface treatment/modification and laser brazing [9]. In order to efficiently utilize advantages of such flexibility of the laser beam, process monitoring [10], intelligent process planning [11] and optimization of process parameters [12] are required.

2.1 Methodology of 3D precision laser micromachining

Effective use of 3D precision laser micromachining technology requires new process planning methodologies different from conventional techniques due to the involvement of a set of different process parameters and their cross-relations. The simplest example is a situation of "cutting air" by using milling tool, as the tool rotates and moves from one location to another there would be no material removal. In the case of laser micromachining, the laser beam will continue to remove material along the tool path trajectory. Such and many similar situations require at its minimum, “adaptation” of conventional 3D machining technologies taking into account specifics of the laser material removal process.

Figure 1 shows a methodology of 3D precision laser micromachining. This methodology inputs a 3D model of the part preferably in STL (stereolithography) format that provides 3D geometry of the part shape. Taking the conventional layer-by-layer machining approach, the 3D geometry is normally sliced into a set of horizontal 2D layers (2½D pockets) introducing initial process parameters such as number and depth (thickness) of layers. These two parameters also determine resulting imperfections of the surface geometry (3D shape accuracy) that can be introduced by stair-like machined surface. Each machined layer is a set of grooves formed by the laser beam, and therefore the machining process is planned for each particular layer taking into account layer-specific parameters such as overlap between grooves, groove tool path trajectory, and width of each groove. All above mentioned process parameters are distinctive for 3D laser microfabrication. Machining of horizontal grooves is a well-established 2D laser machining process where process parameters optimization is focused on required laser power, laser wavelength, pulse repetition frequency, pulse energy and duration, focal distance, feed rate, and spot size. It is important to note that majority of process parameters are cross-related, e.g. number of machined layers determines machining time and reducing number of layers will increase depth of machining and correspondingly decrease shape accuracy.

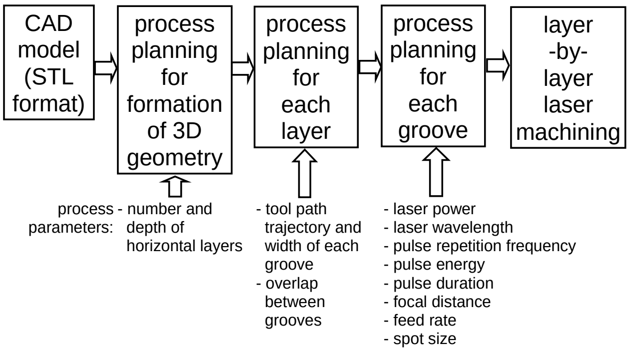
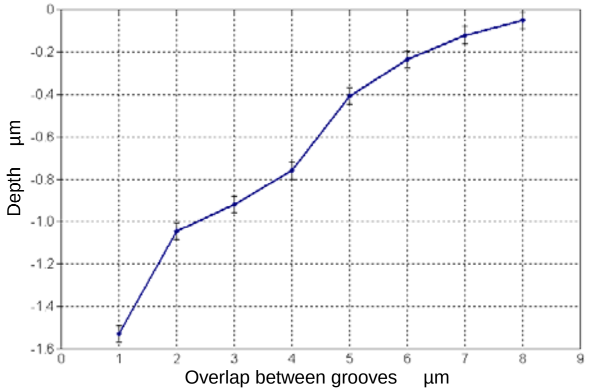


Fig. 1 Methodology of 3D precision laser micromachining.

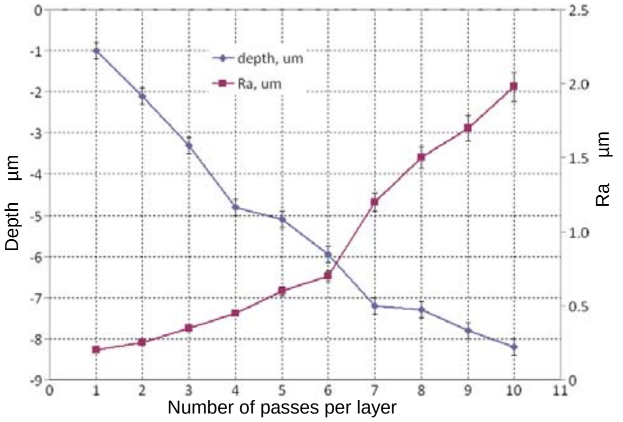
2.2 Effect of process parameters

Several experiments were performed to study the effects of specific process parameters, e.g. overlap between grooves and number of passes per layer, on the geometric quality of 3D machining features. The laser ablation experiments were carried out using a Q-switched, diode pumped, solid-state laser AVIA™ 355-3000 by COHERENT, Inc. with an appropriate beam delivery system and a three-axis positioning system. The laser had a pulse width of 40 ns and repetition rate up to 100 kHz with a wavelength of 355 nm in TEM00 mode (M^2 <1.3). A beam delivery system with a combination of a beam expander and x20 focusing objective was used to focus the laser beam on the workpiece surface with a laser spot diameter of about 16 µm. The motion system consisted of an aluminum base fitted with precision translation stages with air bearings and linear motors for X and Y movements and had a positioning accuracy in the order of 0.1 µm in the X and Y axis. Both the laser and the motion system were controlled and synchronized in time and space. A specimen from mild steel A20 material was used in this study and it was moved at a feed rate of 0.0025 mm/s in the direction perpendicular to the incident laser beam having a pulse energy of 29 µJ. Surface roughness and geometric accuracy/precision were measured using an optical profilometer by VEECO, Inc. with a spatial resolution of 1 Å and an optical microscope OLYMPUS (model PMG3) having an X-Y translation table with a 1 µm positioning accuracy, respectively.

Results of analysis of surface geometry formation with respect to an overlap between grooves and a number of passes per layer are shown in Figure 2. It was found (see Figure 2a) that depth of material removal can be controlled precisely by varying the overlap between grooves, e.g. changing overlap from 1 to 8 µm results in reducing depth of machining from 1.53 µm down to 0.05 µm corresponding to an aspect ratio of 30:1. These results can be used for precision fabrication of shallow 3D structures in dies.



a) depth *vs* overlap between grooves



b) depth and surface roughness *vs* number of passes

Fig. 2 Analysis of surface geometry formation.

It is also necessary to note that each horizontal layer can be machined in several passes in order to achieve desired depth. Figure 2b summarizes the results of experiments where the effect of varying the number of passes per layer was studied with respect to machining depth and surface roughness. These results confirm the presence of traditional compromise between machining time and geometric quality in 3D laser micromachining. Increasing the number of passes per layer led to a decrease in relative machining depth per pass and an increase in surface roughness. The source of such phenomena is in laser modification of optical-physical-chemical properties of the top layer of machined material due to oxidation, accumulation of debris, and other process consequences that have to be taken into account for optimization of process parameters.

2.3 Challenges in 3D precision laser micromachining

Laser micromachining technology has been under development for several years, however, many technical aspects still require further development and improvements for cost effective and efficient industrial applications. These challenges can be summarized in the following list:

- process parameters set-up and multivariable optimization
- accuracy (corners, grooves, overcuts, undercuts, …)
- precision (width, depth, volume of material removed, …)
- surface quality and verticality of walls/cuts
- diagnostics and monitoring of process parameters
- dynamic and kinematic errors of travel motions
- non-uniformity of travel motions, e.g. acceleration
- tool path trajectory planning with respect to dynamics of laser-material interactions
- synchronization of motions and laser on/off events with respect to desired/actual toolpath trajectory in time/space
- modelling of laser-material interactions with respect to desired geometry and machined surface quality

In this study only two major challenges were analyzed during 3D microfabrication – effect of acceleration of motions and dynamic accuracy of motions.

A “Cross Sign” microdie shown in Figure 3 was chosen as a study case to analyze challenges in 3D precision laser micromachining. The die has overall dimensions of 2.5x2.5 mm with “Cross Sign” wall thickness of 50µm and a distance from outer wall of 50 µm all around and made from mild steel A20. Following process parameters were used: laser power - 1.1 W, pulse repetition rate - 40 kHz, feed rate - 0.0025 m/s, number of scans - 250, and an overlap between grooves of 7 µm. As a result, “Cross Sign” die was fabricated with an average surface roughness of 0.35 µm, contour geometric errors within +/-2 µm, with minimum corner radius of 18 µm and with a depth of 48.1 µm (vs 50.0 µm desired depth) having walls with smooth edges and an angle of 96°.

Accordingly the CNC system functioning logic, motion controller sends a signal to turn the laser on or off only after or before motion command is executed causing asynchronization between accelerated motion and laser pulses. Therefore, the laser will be turned on at the beginning of motion, e.g. during acceleration stage, and correspondingly it will be turned off after completing the motion, e.g. during deceleration stage. This leads to extra pulse-density per travel distance during acceleration stage and formation of a deeper cavity, e.g. 10 µm, at the beginning of motions as shown in Figure 4. In order to avoid such situations, proper synchronization of accelerated motions, laser on/off events and the desired geometry need consideration.

Another common problem for any high precision micromachining systems is associated with the dynamic performance of the motion system. However, dynamic performance and associated dynamic accuracy of the tool path trajectory is a key element for achieving the highest accuracy and precision of parts from a particular laser micromachining system. In Figure 5a it can be seen that the motions that form intersection of walls in the “Cross Sign” have significant, up to 13 µm, undershoots (which is 26% of the wall thickness). Such agile situations, in which it is necessary to change the direction of motions abruptly, e.g. sharp corners, create significant dynamic positioning errors due to the inertia of relatively heavy XY translation stages. Conventional CAD/CAM systems do not provide options to correct this issue. The solution consists in modification/correction of an actual tool path trajectory with respect to blending options of a particular motion controller in order to compensate dynamic overshoots or undershoots for a particular cornering trajectory. Figure 5b shows results of implementing this methodology with improved dynamic accuracy up to ±1 µm.

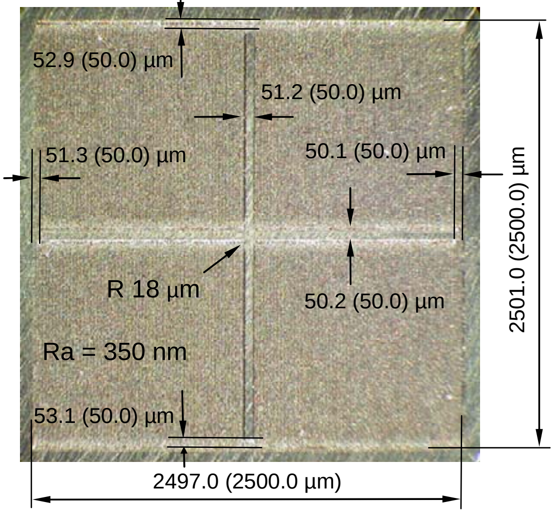


Fig. 3 “Cross sign” die fabricated by laser micromachining

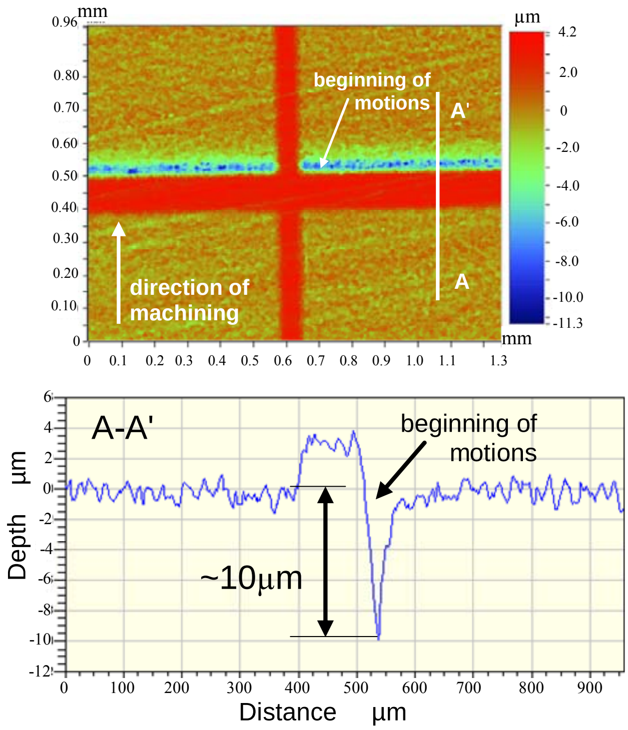
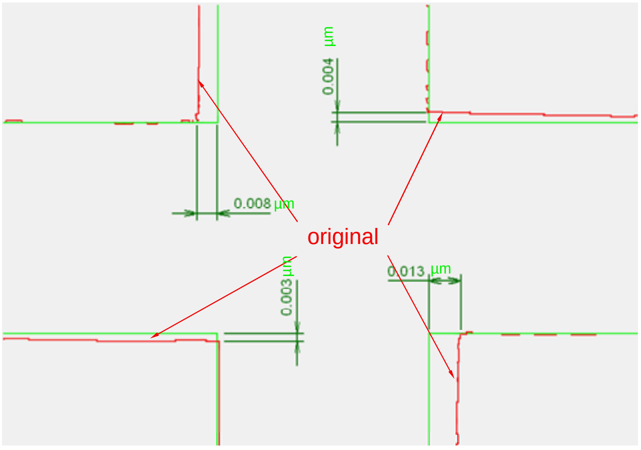


Fig. 4 Effect of asynchronization between motion and laser.

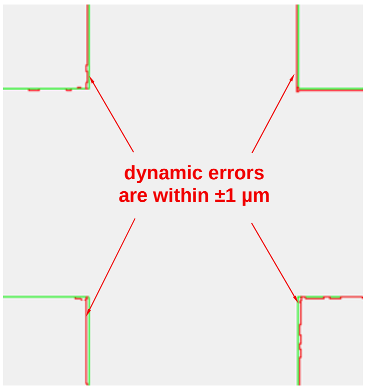
The advantages and disadvantages of using 3D laser micromachining technology for precision fabrication of micro moulds and dies are summarized in Table 1.

Table 1 Advantages/disadvantages of laser micromachining

Advantages	Disadvantages
- highly accurate material removal tool	- laser beam as a cutting tool has uneven geometry which also depends on processing time
- no contact mechanical forces and process vibrations	- significant number of process parameters
- no cutting tool wear and breakage	- not for mass production
- wide choice of materials	- thermal stresses of material
- high precision positioning	- heat affected zone
- maximum process repeatability	- expensive equipment (lasers)
- environmentally friendly	- requires specially trained and skilled operators



a) original (red) *vs* desired (green) tool path trajectory



b) corrected (red) *vs* desired (green) tool path trajectories

Fig. 5 Original and corrected tool path trajectories.

3. Precision micromilling of moulds and dies

The micromilling technology utilizes a combination of a high precision CNC motion system, high speed spindle with a rotational speed up to 250,000 rpm, and miniature cutting tools, micromills, with a diameter as small as 25 µm providing mechanical (by cutting) material removal process at a micro and nano scale. Such combination, especially smaller diameter cutting tools are often comparable to laser focal spot diameter, makes micromilling a competitive process for micromachining of materials. Recent advantages in the development of heat resistant tool coatings further allow use of such cutting tools for cost efficient machining of a variety of materials ranging from plastics to hard-to-machine metals and ceramics.

For comparison purposes, an identical “Cross Sign” microdie (shown in Figure 2) was fabricated from brass using micromilling technology. Micro moulds and dies with similar design structures are widely used for fabrication of plastic microfluidic devices and therefore a replica of the “Cross Sign” in PMMA (polymethyl methacrylate) was produced by hot embossing method.

Described in Section 2.2, the laser micromachining system was additionally equipped with a high speed spindle from KaVo, Inc. having a rotational speed up to 100,000 rpm. A thick brass blank was machined using 200 µm and 40µm diameter micromills for rough and fine machining, respectively. Initially, the main material volume and area around the “Cross Sign” were removed leaving 10 µm along the geometric contour during rough machining with a cutting speed of 0.31 m/s, a rotational speed of 30,000 rpm, and a chip load of 0.25 µm. Same cutting parameters were used for initial facing operation before rough machining in order to prepare a horizontal surface for further rough and fine machining. During fine machining (finishing), the remaining 10 µm were removed along the contour of the geometry in order to achieve final contour accuracy and precision with minimum radius of angular features, e.g. corners, with a cutting speed of 0.08 m/s, a rotational speed of 30,000 rpm and a chip load of 0.04 µm.

Figure 6 shows a “Cross Sign” microdie fabricated by micromilling along with the accuracy and precision of geometric features achieved, e.g. wall thickness and distance to outer contour, are shown in Figure 6a and a wall cross-section and surface roughness are shown in Figures 6b and 6c/6d, respectively. A surface roughness, Ra, of 158.4 nm was achieved during machining of quadrants (areas between “Cross Sign” and outer contour). The final geometric contour was machined with an accuracy and precision within ±1 µm and a minimum corner radius of 26 µm. “Cross sign” die was machined with a depth of 50.3 µm (vs 50.0 µm desired depth) having almost vertical walls with an angle of 95° which is a result of the cutting tool radial deflection during final contouring operation. It is also necessary to note significance of direction of machining in formation of surface roughness, which is two times better along machining, Ra = 80.1 nm vs across direction of machining, Ra = 158.4 nm (see Figures 6c and 6d). This fact was taken into account and top surfaces of “Cross Sign” were machined along its primary geometric direction with a surface roughness of 80.8 nm before polishing. The top surface of the “Cross Sign” was manually polished in order to remove burrs with a height of about 1 µm and improve surface roughness, Ra, from 80.8 nm down to 46.1 nm. In general, the surface roughness depends on a number of parameters: the quality and wear of the tool, the spindle’s rotational speed and run-out, and the type of material. In this case, an average roughness Ra below 100 nm was readily obtained. Through optimization of the material removal process, optical quality surfaces with Ra below 50 nm can be obtained.

Micromilling technology become accessible lately due to recent advances in downsizing of cutting tools and advanced coatings. However, classical machining theory does not fully encompass nano/micro-scale material removal. In addition, available CAM software packages for high speed machining and process planning, still need to address the following machining challenges:

– process parameters optimization with respect to tool deflection, wear and breakage
– process planning and optimization with respect to plunging, machining of internal corners, full width machining and continuous tool engagement
– machining thin structures and geometric features with high aspect ratio

The advantages and disadvantages of micromilling technology for precision fabrication of micro moulds and dies are summarized in Table 2.

Table 2 Advantages/disadvantages of micromilling

Advantages	Disadvantages
- highly accurate material removal tool - constant diameter and specific length of the cutting tool - few process parameters - suitable for mass production - wide choice of materials - high precision positioning - inexpensive equipment (spindle) - no thermal stresses of material - average skilled operators	- contact mechanical forces and process vibrations - tool deflections/wear/breakage - no methodologies for process parameter optimization - no methodologies for reliable and breakage-free tool path trajectories - dependable repeatability - costly micro tools (<0.1 mm) - complex tool alignment - limitation in machining of sharp corners

Figure 7a shows a replica of machined "Cross Sign" die in PMMA made by hot embossing process in order to analyze geometric quality of rectangular microfluidic channels. The PMMA substrate was placed between heated platens of the manual hot press equipped with a load cell made by International Crystal Laboratories, Inc. and then heated up to a temperature of 120ºC, which is slightly above a PMMA glass transition temperature of 105ºC. Then, a load of 500 N was applied for 10 min to press the die into PMMA substrate to replicate the "Cross Sign" geometry. Figure 6a shows a photograph of embossed 3D geometry confirming optical clarity and absence of visual defects and/or surface irregularities. Replicated rectangular channels were visualized with scanning electron microscope (SEM) (see Figure 7b) and cross-section and surface roughness of channels were analyzed by using optical profilometer. Microfluidic channels were fabricated with ±1 μm accuracy and precision, e.g. a measured width of 49.1 μm *vs* a desired width of 50 μm and a measured depth of 49.2 μm *vs* a desired depth of 50 μm (see Figure 7c), and with a roughness of the channel surface of Ra = 9.9 nm *vs* 46.1 nm on the top of "Cross Sign" walls.

4. Summary and conclusions

Each material removal process, laser micromachining and micromilling, has its own advantages and disadvantages, e.g. laser micromachining can deliver higher material removal rate over micromilling, however it can not be used for machining vertical walls and to achieve surface roughness <50 nm. The laser micromachining and micromilling technologies are promising cost-efficient microfabrication methods for micro mould and die manufacturing.

The following conclusions can be drawn from these studies:

– laser microfabrication is a complex layer-by-layer material removal process and involves a number of cross-related process parameters which influence the geometric quality of the machined parts.
– effect of 3D laser micromachining specific parameters, such as, overlap between grooves and number of passes per layer was analyzed to control the depth of material removal down to 0.25 μm/layer.
– laser micromachining is capable of fabricating near vertical walls with smaller corner radius, e.g. 18 μm *vs* 26 μm, having wall verticality comparable to micromilling.
– the final accuracy of the fabricated "Cross Sign" die geometry is a result of a complex combination of the positional accuracy and dynamic accuracy of motions.
– in order to achieve highest accuracy and minimize volumetric errors, laser performance has to be controlled and synchronized with motions in time and space, simultaneously.
– micromilling process offers unique and complimentary advantages to 3D precision laser micromachining technology. In order to capitalize on these advantages, a hybrid combination of both processes may be beneficial for specific mould and die applications.
– studied technologies open new engineering and commercial opportunities in design and fabrication of micro moulds and dies for biomedical, automotive, electronic, and other industrial applications.

Acknowledgment

The authors are grateful to their colleagues, Matthew Shiu, Hugo Reshef, and Marco Zeman, for help in performing the laser micromachining and micromilling experiments.

References

[1] T. Hanemann, K. Honnef and J. Hausselt: Int. J. Adv. Manuf. Technol., 33, (2007) 167–175.

[2] H. Klank, J. P. Kutter and O. Geschke: Lab Chip, 2, (2002) 242–246.

[3] M. Bowden, O. Geschke, J. P. Kutter, and D. Diamond: Lab-on-a-Chip, 3, (2003) 221–223.

[4] J. J. Chang, B. E. Warner, E. P. Dragon, and M. W. Martinez: J. Laser Appl. 10(6), (1998) 285–291.

[5] F. Bundgaard, G. Perozziello and O. Geschke: Proc. IMechE Part C: J. Mechanical Engineering Science, 220, (2006) 1625-1632

[6] E. V. Bordatchev and S. K. Nikumb: Machining Science and Technology: An International Journal, 7(1), (2003) 83-104.

[7] J. Higgins: Laser Focus World, (2001) 183-186.

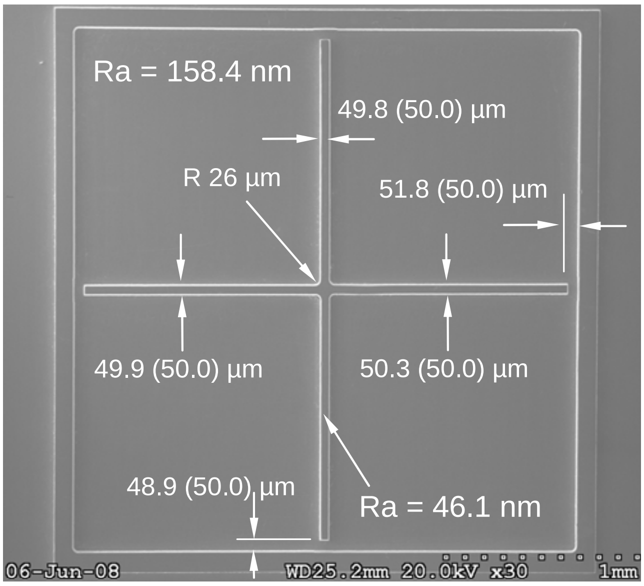
[8] "3D Laser Precision Microfabrication" ed. by H. Misawa and S. Juodkazis, (Wiley-VCH, Weinheim, 2006) p.403.

[9] W. M. Steen and K. Watkins: "Laser Material Processing" (Springer-Verlag, London, 2003) p.408

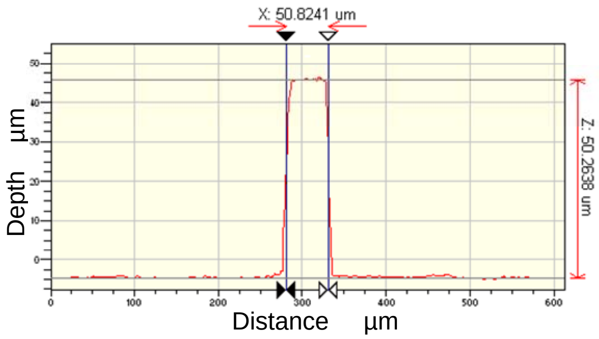
[10] E. V. Bordatchev and S. K. Nikumb: J. of Applied Surface Science, 253, (2006) 1122-1129.

[11] E. Mutapcic, P. Iovenitti and J. P. Hayes: Microsyst Technol., 12, (2005) 128–136

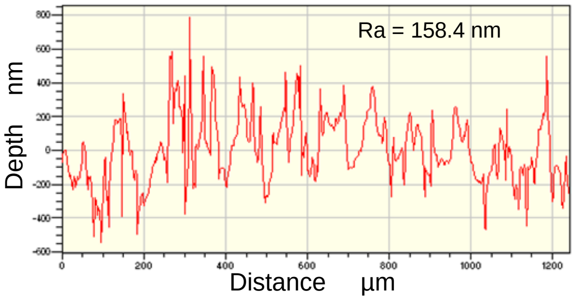
[12] P. Bartolo, J. Vasco, B. Silva and C. Galo: Assembly Automation, 26/3 (2006) 227–234



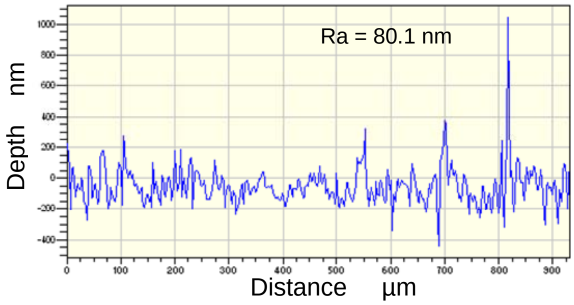
a) geometry and accuracy



b) wall cross-section and surface roughness

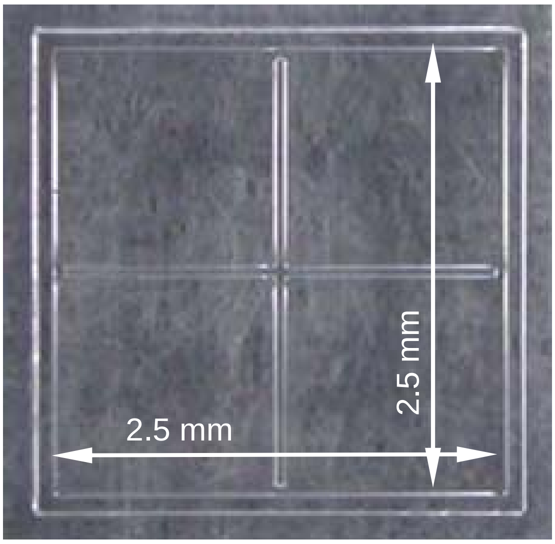


c) surface roughness across direction of machining

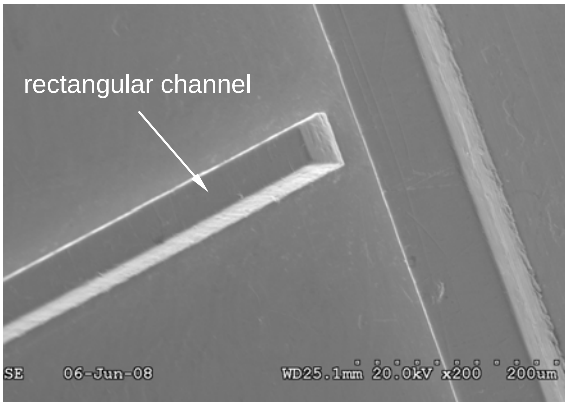


d) surface roughness along direction of machining

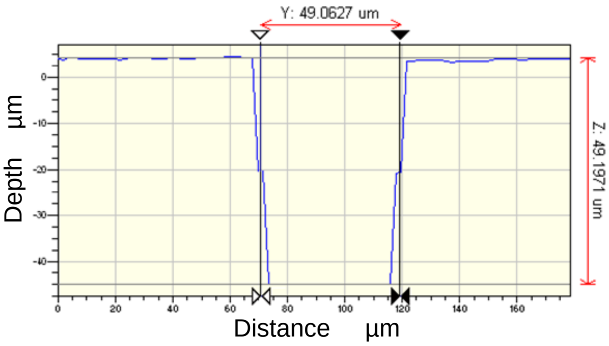
Fig. 6 “Cross Sign” microdie fabricated by micromilling.



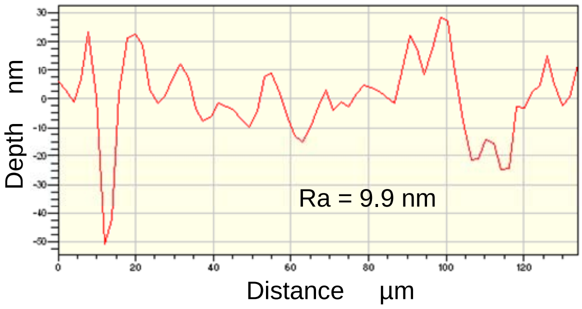
a) photograph of 3D geometry



b) SEM photograph of rectangular channel



c) cross-section of the channel



d) surface roughness inside the channel

Fig. 7 Replica of “Cross Sign” hot embossed in PMMA.

(Received: June 16, 2008, Accepted: November 25, 2008)